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COMPOSITE WALL STRUCTURE FOR ENHANCED MAGNETIC SHIELDING

FIELD OF THE INVENTION

The present invention relates to shielding of sensitive devices against the magnetic interference in their environment. Examples of devices requiring electromagnetic shielding specifically against magnetic fields are ultrasensitive measuring devices like SQUID-based magnetometers used in biomagnetism, or E-beam devices used for fabrication of nano-scale thin film structures in semiconductor industry. These devices are typically operated in urban areas close to sources of strong magnetic interference such as trains and cars - causing interference predominantly in the low frequency domain below one Herz - and digital electronic equipment and computers emitting radiation at higher frequencies up to the megaherz range.

DESCRIPTION OF THE RELATED ART

The easiest way to achieve magnetic shielding is to construct a coil system – three orthogonal Helmholz coils, say – around the volume to be shielded. The currents fed to the coils to compensate the magnetic interference are controlled by signals from a magnetometer, for example a three axis flux gate. The magnetometer can be placed either at a distance outside the coil system, if the interfering field is known to be predominantly uniform, or inside the coil system close to the instrument to be shielded.

These techniques are examples of *active shielding*. The major advantages of active shielding are low cost and low weight. The performance of active shielding is, however, limited by the performance of the control system. The finite number of coils used for compensation are able to generate compensating fields of certain geometric shapes only. Therefore, an interference field of complicated geometry over a large volume can be only partially compensated. Even if this geometric performance of the system would be sufficient, the degree of active compensation is always limited by the intrinsic noise level and operation band of the magnetometer that provides the actuating signal.

Because of these limitations the active shielding is often supplemented or even replaced with *passive magnetic shields* typically made of materials having either a high magnetic permeability or a good electrical conductivity. The high permeability material shields the surrounding space by getting strongly magnetized which leads to appearance of an induced field counterbalancing the magnetizing interference field in the vicinity of the magnetized material. Effectively this corresponds to "focusing" of the magnetic flux from the surrounding into the material itself.

The shielding provided by a good conductor is based on a rather different mechanism. Owing to the good conductivity strong eddy currents are provoked in a conductor exposed to a varying magnetic field. The magnetic field associated with these induced currents counteracts the interfering magnetic field. The conductivity being finite leads to damping of the induced currents so that this mechanism contributes to shielding only at higher frequencies and is totally ineffective at DC.

An example of a passive shield is a Magnetically Shielded Room (MSR) commonly used in biomagnetic measurements. Tens of such rooms of different size and construction have been built during the last fourty years. There are rooms made of thick plates of plain Aluminum ("Thick-walled conducting shield in biomagnetic experiments", J. A. V. Malmivuo, P. Heinonen, M. Tuomola, and J. Lekkala, in Biomagnetism, eds S. N. Erne & al. 1981, WdG, Berlin, pp. 107-112), as well as rooms made almost exclusively out of high permeability Ni/Fe-alloys ("The 8-layered magnetically shielded room of the PTB: Design and construction", J. Bork, H.-D. Hahlbohm, R. Klein, and A. Schnabel, 12th International Conference on Biomagnetism, Helsinki, 2000). Most commercial rooms consist of several nested shells made of either Aluminum or Ni/Fe plates, or Ni/Fe plates on Aluminum.

These rooms are used in practically every laboratory or hospital making biomagnetic recordings of either the central nervous system or the heart of human subjects because, as compared to active compensation arrangements, a properly constructed MSR is a simple brute-force method of magnetic shielding for the large volumes necessary for these applications.

A simple way to characterize the performance of an MSR quantitatively is to define the frequency dependent shielding factor, $S(f)=B_o(f)/B_i(f)$, where B_o is the density of magnetic flux outside MSR and B_i is the flux density inside the room, for example at the center. The shielding factor defined in this way is a dimensionless scalar quantity and its numerical value may also be given in decibels: S in dB = 20*Log(S).

The frequency spectrum of the magnetic interference $B_o(f)$ in a typical urban environment follows the 1/f rule in the range 0,1 ... 100 Hz which is relevant for the biomagnetic applications. Therefore, the highest shielding factor would be needed at the low frequency end below one Herz. Since eddy current shielding is ineffective at low frequencies the conductive wall material does not play any role in this most important frequency range. Thus, to guarantee sufficient shielding performance the prior art has mainly concentrated on optimizing the ferromagnetic shielding.

It has been shown by calculations and demonstrated experimentally (for example "Design, Construction, and Performance of a Large-Volume Magnetic Shield", V. O. Kelhä, J. M. Pukki, R. S. Peltonen, A. J. Penttinen, R. J. Ilmoniemi, and J. J. Heino, IEEE Trans on Magnetics, Mag-18, no. 1, 1982, and references therein) that given a fixed amount of ferromagnetic material with a given magnetic permeability the way to maximize the low frequency shielding factor is to devide the ferromagnetic material into successive nested shells so that the volume of the

outer shell is clearly larger than the volume of the next inner shell. The inner shell being much smaller and basically exposed to the field at the center of the outer shell leads to the total shielding factor, S_t, being close to the product of the shielding factors of the individual shells.

If the second shell were simply layered on top of the first one the total shielding factor would be the sum of the two shielding factors only. Typically, for a single ferromagnetic shell of reasonable thickness S=10, so that a sufficient gap between the two shells leads to S_t•10*10=100, whereas using the same amount of material in a single wall of double thickness gives S_t•10+10=20 only.

This way of thinking has led to very large and heavy MSR designs, especially because in the biomagnetic application the space requirement inside the innermost shell is already about 3*4*2,5 m^3. The total wall thickness of a three shell MSR having two sufficiently wide gaps between shells may well be about 50 cm. Such a multi-shell MSR may weigh about ten tons and can be installed in a double floor space only, because of the 3,5 m height. It is expensive and requires a complicated door construction; a slow-to-operate multiple door arrangement may be necessary when more than two shells are used. These are the main disadvantages of the prior art.

SUMMARY OF THE INVENTION

This invention relates to optimal way of technically combining the two types of magnetic shielding mechanisms and materials – soft ferromagnetic materials and highly conductive eddy current materials - into a compact wall element having maximal shielding efficiency.

The invention is motivated by the need to reduce the size, weight, complexity, and cost of magnetic shield, especially MSRs. Therefore, the composite wall element described is intended to be used in single shell MSR constructions, but it is also the optimal element in the individual shells of a multi-shell magnetic shield.

The reasoning behind the invention is quided by model calculations the results of which are shown in Fig. 1. These calculations of the shielding factor S(f) of different wall compositions are made with the Shielding Matrix method ("Magnetic shielding factores of a system of concentric spherical shells", J. Appl. Phys. 33, no 3, 1967). The method is based on the analytic solution of Maxwell equations for concentric spherical shells made of materials with given electrical conductivity and relative permeability, and exposed to a uniform external magnetic field. The fact that the typical shape of magnetic shields and MSRs is rather a rectangular parallelepiped than a sphere is taken into account by modifying the demagnetization factors in the Shielding Matrix method in a way commonly used in the litterature (see for example Kelhä & al.).

Aluminum and Mumetal (a Ni/Fe alloy, trademark of Vacuumschmelze GmBH) are used in these calculations as examples of conductive and ferromagnetic

materials with relative permeabilities 1 and 16000, and conductivites $3{,}57*10^7$ and $1{,}82*10^6\,(\Omega m)^{-1}$, respectively. The size of the MSR is $3*4*2{,}4\ m^3$, and the shield is assumed to have a $5*5\ cm^2$ hole for feedthroughs. It is the field leaking through this hole that limits the shielding factor of the best wall structures to the level of about 114 dB in Fig. 1.

In the examples calculated the amount of expensive and heavy Mumetal is limited to a total thickness of 2 mm and the combined weight of the wall elements to below 3000 kg, which allows using a total thickness of 12 mm of Aluminum in the wall. In all the cases shown in Fig. 1 the successive layers of Mumetal and Aluminum are assumed to be in contact. This corresponds to the central idea of the present invention; to find an optimal integral wall element or module that can be prefabricated in the factory before the final assembly into a light weight MSR at the installation site.

The two lowermost curves in Fig. 1 show S(f) for the rooms with walls made of plain Aluminum (12 mm) and plain Mumetal (2 mm). As pointed out above the shielding efficiency of plain Aluminum is negligible at low frequencies. The eddy current shielding starts to show up between 0,1 and 1 Hz and increases steadily toward higher frequencies.

The S of the plain 2 mm Mumetal wall is 21 dB at low frequencies. This shielding effect results entirely from the focusing of the magnetic flux into the wall. The focusing of flux does not increase with increasing frequency; the phenomenon eventually *decreases* beyond about one kiloherz because of decreasing dynamic permeability. The rise of S with frequency in the plain Mumetall wall is entirely due to the eddy current effects which start to show up at frequencies above 10 Hz. This regime of shielding enhancement is higher in frequency by a factor of ten compared to the case of Aluminum, because the conductivity of Mumetal is by factor twenty lower than that of Aluminum.

From about 20 Hz on the increase of S is clearly steeper for Mumetal than for Aluminum. This may be explained by the interplay between the focusing-of-flux and eddy-current mechanisms: the focusing boosts the eddy current damping by enhancing the AC flux density of the magnetic field in the metal. In plain Aluminum the focusing is absent.

As seen from Fig. 1, the rise of S with increasing frequency in the high permeability material is extremely steep above 100 Hz; S increases by more than a factor of 100 when the frequency rises from 100 to 300 Hz. This steep a rise could be made to happen at lower frequencies by increasing the conductivity of the high permeability material. This is clear from the formulas of the Shielding Matrix Model where the conductivity appears only as a factor multiplying the frequency. The uppermost curve in Fig. 1 shows the shielding factor that is obtained with a 2 mm wall of fictitious "MuAluminium" having the permeability of Mumetal but a conductivity corresponding to the combination of 2 mm of Mumetal and 12 mm of Aluminum.

"MuAluminium" does not exist but one can mimic its function by a technically feasible wall structure, a sandwich consisting of interleaving and alternating

sheets of high permeability material and highly conductive material. This is the central innovation in this invention. The shielding factors obtained for the three Mu/Al sandwich structures (Fig. 1) indicate that the enhanced eddy current damping of the AC magnetic field, intensified because of flux focusing, considerably improves the shielding at frequencies above 0,1 Hz. The central invention, differing from the prior art, is the division of the ferromagnetic material in the wall element into several separate layers placed around or in between the plates made of the highly conducting wall material.

The interplay between the two shielding mechanisms is already obvious from the third S(f)-curve in Fig. 1, describing a composite wall of 2 mm Mumetal inside and 12 mm Aluminum outside: The shielding factor of this wall structure exceeds the product of the shielding factors of 2 mm of plain Mumetal and 12 mm of plain Aluminum at all frequencies above 0,03 Hz. Here the enhancement of shielding owing to the interplay between the two mechanisms is maximal around 4 Hz where it reaches 9 dB (factor 2,8).

This kind of a bilayer composite wall has been used by some room makers. Aluminum has been considered to be necessary for rf-shielding anyway, and Aluminum plates have provided handy means of supporting the thin 1 mm Mumetal sheets. This structure must be considered as part of the prior art.

As is seen from Fig. 1, already by simply deviding the 2 mm of Mumetal in this prior art wall structure into two 1 mm sheets placed on opposite sides of the 12 mm Aluminum plate enhances magnetic shielding by more than 10 dB in the range 0,2 ... 10 Hz. Distributing the same total amount of ferromagnetic material even more uniformly among the conducting material – like in the Mu/Al-composite structures 1/6/1/6, and 0,5/3/0,5/3/0,5/3/0,5/3 mm in Fig. 1 - leads to further enhancement of shielding at frequencies above 0,5 Hz.

Deviding the ferromagnetic material into thinner and thinner plates distributed evenly among the Aluminum would raise the shielding factor toward the uppermost "MuAluminium"-curve in Fig. 1. This indicates that a sandwich made of alternating high permeability and high conductivity plates really mimics "MuAluminium": it functions like a highly conductive ferromagnetic shielding material.

The large gaps between the shells of different shielding material – characteristic to the multi-shell MSRs of prior art – do improve shielding at DC, but do not have a significant effect on the interplay of the two shielding mechanisms at higher frequencies. This is seen by comparing the shielding factors for the 1/6/1/6 mm sandwich and a similar but thicker wall where the successive four layers are separated from each other by 17 cm. The latter design leads to a prior art style room having one meter larger outer dimensions in all three directions. At DC where the eddy current shielding mechanism is absent the latter design has a shielding factor higher by about 5 dB, but above 0,5 Hz the shielding provided by the sandwich wall actually *exceeds* that of the thicker wall by 2 dB. Obviously, because of the closer contact between the ferromagnetic and conductive layers the sandwich wall shows a stronger "MuAluminium"-effect that boosts shielding above 0,5 Hz.

This indicates that it is always advantageous to mix ferromagnetic and conductive materials in the shells of a shielding room, even in multi-shell MSR designs. This idea is new compared to prior art where separate Aluminum shells are included among the Mumetal shells, primarily because Aluminum - being an excellent conductor compared to Mumetal - provides good shielding against rf interference. The 26 ton room constructed at PTB in Berlin (Bork & al.) includes among its eight shells only one Aluminum shell that is separate from the seven other shells made of plain Mumetal. This design may be optimal close to DC, where Aluminum is irrelevant but at higher frequencies a compromise leaving out some of the Mumetal and replacing it with interleaving plates of Aluminum would provide better shielding.

To compensate for the loss of shielding efficiency at low frequencies when changing from a multi-shell room into a single shell sandwich wall active compensation may be used. Working with a narrow banwidth below 10 Hz, say, the internal noise level of the actuating sensor, and the phase shifts associated with the surrounding conducting material are not a problem, and a reasonable amount of interference suppression is achievable with an active compensation coil arrangement the cost of which is a fraction of what one or two extra shells of an MSR would cost.

All the calculated results referred to above are valid for ideal closed nested shells only. The overall geometry of the shielding shells is crucial for both the flux focusing and the eddy current mechanisms; only a closed ferromagnetic shell geometry is free of any edges of the shield that would affect the flux focusing, and the "global" eddy currents around the entire conductive shells essentially contribute in the eddy current shielding mechanism.

This fact has two consequences from the point of view of design and construction of magnetic shields. First, the shielding efficiency of a given wall structure cannot be found out by making calculations, or experiments, with a simple plane geometry; the shielding factor calculations can be verified only by comparing with the shielding factor measurements made on closed shields, either small scale models or existing rooms. Second, in the actual design of the shield the ferromagnetic and electric continuity of each layer must be quaranteed.

The technical realizations of the shielding layers in the prior art MSRs as well as in the present invention consist of ferromagnetic and conductive elements with non-ideal joints between them. These joints represent extra resistance and magnetic reluctance in the shells which must be taken into account as reduced effective values of permeability and conductivity in the Shielding Matrix model calculations.

Comparison of the shielding factors calculated with the Shielding Matrix method with the measured S(f) of several prior art rooms shows that - with the techniques available at present - properly designed and realized joints between wall elements effectively reduce the conductivity of the Aluminum shells by less than 20%, and the effective dynamic permeability values of the ferromagnetic plates from the

20000 ... 30000 range, given by the vendors of the raw material, down to about 15000 ... 23000.

To keep the effective permeability this high a low enough magnetic reluctance in the joints between the ferromagnetic elements is required. For this an overlap area between adjacent elements as wide as possible is desirable. The requirement is fulfilled in the ferromagnetic shells of prior art rooms by stacking two or more layers of thin Mumetal sheets on top of each other so that the joints of the first layer are overlapped by the sheets of the next layer. In some designs crossing layers of Mumetal sheets on top of each other have been used (for example Kelhä & al.). These methods of securing low magnetic reluctance naturally lead to the asymmetric prior art Mu/Al-wall structure referred to above (see Fig. 1), but are not consistent with the sandwich wall element concept of the present invention.

To reach a sufficiently low magnetic reluctance with the element costruction of the present invention a double sided joint structure like that shown in Fig. 3 is necessary. The joint between adjacent ferromagnetic sheets must consist of an overlap area several centimeters wide. The joining plates must be pressed together so that the gap between them in the overlap area is minimized.

To achieve good continuity for the conductive shells the Aluminum layers of adjacent elements must have overlapping contacts of at least a few centimeters wide and provided with some kind of conductive paste or EMI gaskets. In some prior art rooms an ideal electrical continuity has been achieved by welding the Aluminium elements into an integral shell (Kelhä & al.). This method can not be used with sandwich wall elements.

An example of a wall element according to the present invention is shown in Fig. 2. The elements are identical, except length; a few longer ones are needed for the roof and the floor if the width of the room is more than its height. A room assembled from such integral wall elements, especially if it comprises one shell only, is quick to install, and disassemble and move to an other location when needed.

The preassembling of these elements at the factory can be automated. This minimizes the handling of the separate thin ferromagnetic plates and prevents the reduction of their permeability resulting from harsh mechanical handling. In the final element the Aluminum plate between the two ferromagnetic ones reaches further out and protects them during further handling and assembly of the MSR.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1. Examples of calculated shielding factors S(f) of rooms having different wall structures consisting of layers of high permeability and high conductivity metal plates. The plain Mu, plain Al, and the two layer Mu/Al wall structures are characteristic to prior art.
The Mu/Al/Mu, Mu/Al/Mu/Al, and Mu/Al/Mu/Al/Mu/Al/Mu/Al structures, all composing of the same total amount of Mumetal and Aluminum per square meter of wall, are embodiments of the present invention. The total thickness of Mumetal and Aluminum in all the composite Mu/Al wall structures are 2 and 12 mm, respectively.
The uppermost "Mualuminium" curve is calculated for a wall made of fictitious material having the permeability of Mumetal and the total conductivity corresponding to 12 mm of Aluminum. This curve is the asymptote that is approached but never reached when the Mumetal and Aluminum in the composite wall are devided into finer and finer interleaving sheets.

Fig. 2. The structure of the sandwich wall element for a magnetic shield.

Fig. 3. A cover strip used to ensure layer-by-layer magnetic and electric continuity between the sandwich wall elements of Fig. 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The composite magnetic shield according to the present invention works as indicated in Fig. 1 only if the magnetic and electric continuity is taken care of in each and everyone of the subshells of the sandwich wall. Stacking up the wall elements using a very large number of separate sheets is laborious, and the thickness tolerances tend to prevent achieving the required electric and magnetic contact in the joints between the elements. This makes the extreme sandwich structure - made of very many thin metal sheets, and having the best shielding properties - rather impractical.

Therefore, the simple four layer element shown in Fig. 2 is described as the preferred embodiment. In this case each element consists of four rectangular metal plates mounted face-to-face by gluing or mechanically. The plates are cut to such dimensions that when stacked concentrically, all the edges of the element have the structure shown in the close-up in Fig. 2. The Aluminum plate (1) reaches out from between the ferromagnetic plates (2) and (3). This protects the ferromagnetic plates mechanically during the handling of the elements. The exposed Aluminum surface also serves as the electrical contact with the cover strip (6), see Fig. 3. The outer ferromagnetic plate (2) is further covered with the second Aluminum plate (4) that leaves the edges of plate (2) uncovered for ferromagnetic contact with the

cover strip. To match the edges of the element properly with the cover strips thin layers of soft dielectric matérial (5) may be inserted between the plates.

The wall-to-wall, wall-to-floor, and wall-to-ceiling corners of the room require special elements. The structure of these elements is identical with the ordinary wall elements except that they may be narrower and are bent by 90 degrees along their longer central line, shown dashed in Fig. 2. The relatively thick Aluminum components of such corner elements are preferably made of symmetric L-profiles, whereas the ferromagnetic plates needed are bent and heat treated after bending.

The means of joining these wall elements having double ferromagnetic layer is shown in Fig. 3. Two cover strips (6) on both sides of the wall are used. These strips may be but do not need to be identical. The composite strips consist of narrow plates of Aluminum (8) and ferromagnetic material (9). Two thin plates of elastic material (7) are used as springs to secure good contact with wall elements for both aluminum ànd ferromagnetic layers, independent of thickness tolerances of the plates involved. For mechanical protection, the cover strips are mounted on the aluminum U-beams (10 and 11) before transportation and handling at the installation site. This may be done by small screws the heads of which fit in the gap between the two wall elements. The holes for these screws as well as the larger holes for the bolts used in the assembly of the room are made before heat treatment of the ferromagnetic strips. No holes are needed on the proper wall elements except the penetrations needed for ventilation of the room and technical feedthroughs required by the device in the room.

When assembling the room the beams on the outside (11) also serve as the supporting frame. The wall elements are placed against these frame beams - which have the pre-mounted cover strips on them- and clamped in place by using. the inside U-beams (10) with cover strips. The bolts used in clamping go through the premade holes on both beams and the cover strips, and through the gap between the wall elements which is slightly wider than the bolt diameter.

The electrical continuity of the outermost Aluminum layer (4) may be taken care of by the beams (11) of the supporting frame, or by an additiuomnal aluminum strip integtrated on top of the cover strip in case the beams are made of low conductivity metal like steel.

To ensure the electrical continuity of Aluminum layers EMI-gaskets may be used between the Aluminum parts of the wall elements and cover stripes. The extra space needed for the gaskets is obtained by adjusting the thickness of the elastic layers (7).

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CLAIMS

1. A wall structure to be used for magnetic shielding, **characterized** in that the wall is formed by a composite including interleaving layers of high permeability material and layers of high conductivity material .

2. A wall structure according to claim 1, **characterized** in that the layer of high permeability material between the sheets of high conductivity material is not continuous but made of pieces of high permeability material or high permeability plate.

3. A composite wall according to claim 1 or 2, **characterized** in that the wall consists of elements in which the high permeability material is devided into two or more different layers separated by layers of high conductivity material.

4. A composite wall element according to claim 3, **characterized** in that at all the edges of the element one of the high conductivity layers reaches out further than any of the high permeability layers.

5. A composite element according to claims 3 and 4 to be used in the magnetic shields, **characterized** in that the sheets of high conductivity material and the sheets of high permeability material forming the element are bent along a line to form a corner of a magnetic enclosure.

6. A magnetic shield constructed of wall elements according to claims 3 and 5, **characterized** in that the elements are integrated to form the walls, ceiling and floor of the shield by using composite cover strips that have a matching sequence of interleaving highly conductive and high permeability layers for connecting the wall elements so that the electrical continuity of each of the high conductivity layers and the magnetic continuity of each of the high permeability layers is obtained.

7. Cover strips according to claim 6 to be used in the construction of a magnetically shielding enclosure **characterized** in that a layer or layers of elastic material are placed between two or more of the successive layers in the strip.

8. A magnetically shielded room **characterized** in that the walls of the room consist of one or several nested shells constructed of the composite elements according to claims 3 and 5, and of the cover strips according to claim 6.

9. An instrument shield for protection against magnetic interference **characterized** in that the shield is formed by one or several composite elements having the structure described in claim 1 or 2.

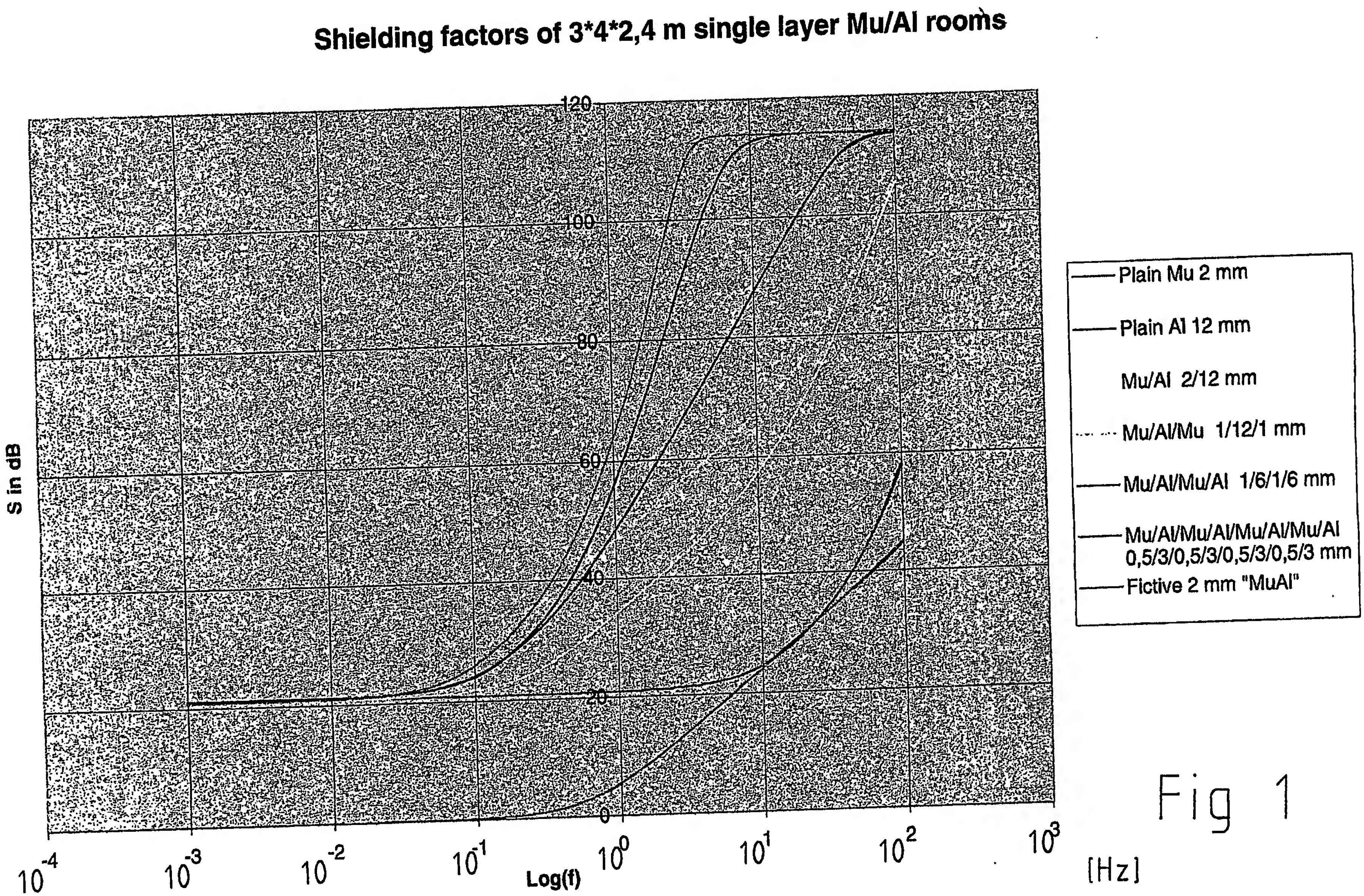
Shielding factors of 3*4*2,4 m single layer Mu/Al rooms
S in dB
120
100
80
60
40
20
0
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
Log(f)
[Hz]
Plain Mu 2 mm
Plain Al 12 mm
Mu/Al 2/12 mm
Mu/Al/Mu 1/12/1 mm
Mu/Al/Mu/Al 1/6/1/6 mm
Mu/Al/Mu/Al/Mu/Al/Mu/Al 0,5/3/0,5/3/0,5/3/0,5/3 mm
Fictive 2 mm "MuAl"

Fig 1

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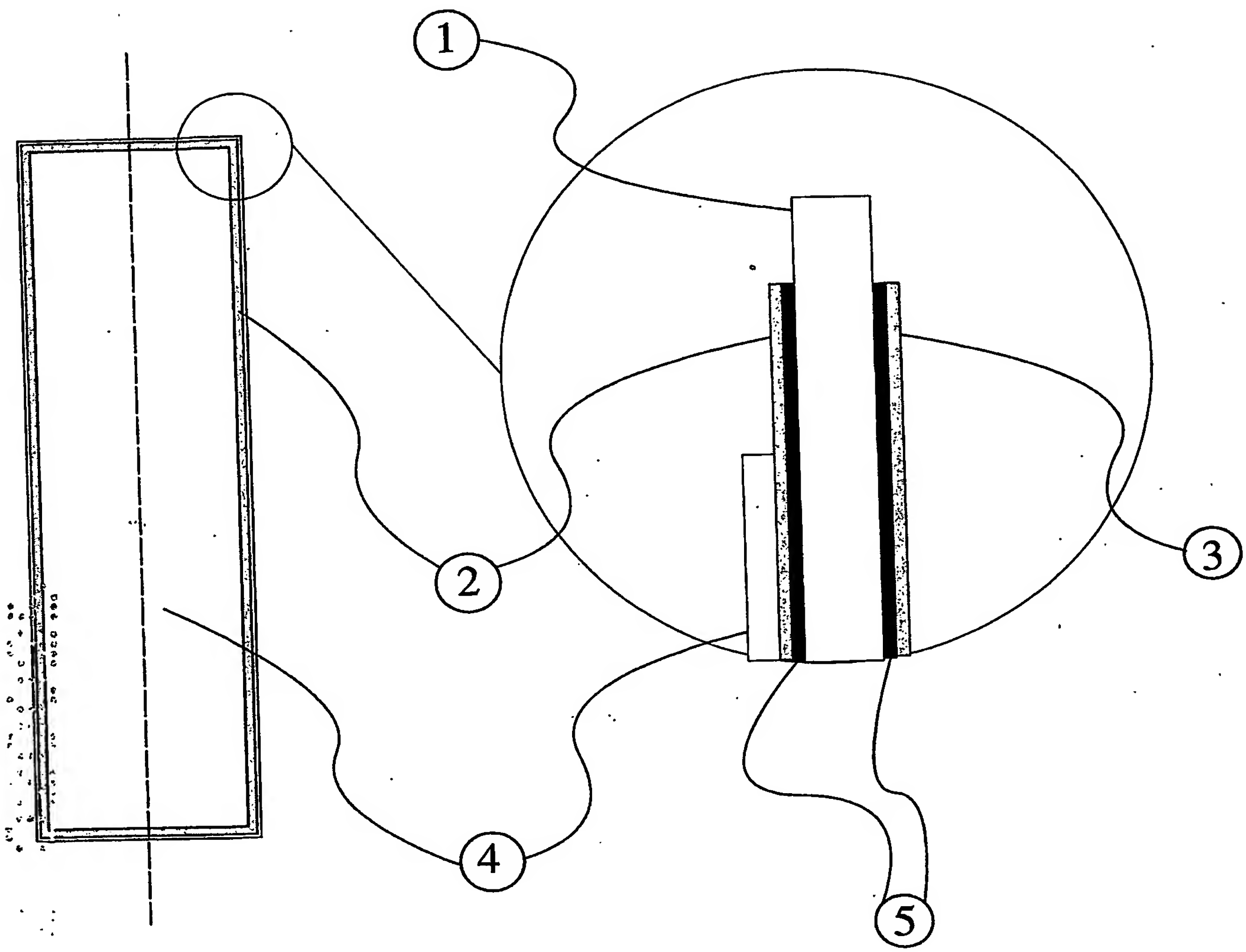
Fig. 2



L 3

Fig. 3